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Practical experiences on applying substance flow analysis in Flanders: bookkeeping and static modelling of chromium

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Abstract

Substance flow analysis is one of the analytical tools applied in the research field of industrial ecology. This paper presents practical experiences on implementing substance flow analysis to support integrated environmental policy in the Flemish region of Belgium. We have studied the case of chromium flows within the regional economic system, within the regional ecosystem and among these interdependent systems. During the project, a bookkeeping account and a static model were constructed. Origin analyses and sensitivity analyses were used and calculations on the effects of potential policy measures were carried out. The analyses and calculations show that many difficulties exist in connection with the substance being studied on the one hand and the region under investigation on the other. The contribution as well as the practical difficulties and limitations of applying substance flow analysis are presented.

Keywords: Industrial ecology; Substance flow analysis; Chromium; Flanders

1. Introduction

In industrial ecology, the earth functions as a materially closed system with a limited amount of available resources and a limited capacity to handle waste. Whereas the biological system has evolved into a closed materials cycle that relies on renewable resources and is capable of handling its own waste products, the industrial system clearly has not [1]. In the pursuit for sustainable development, the aim is to develop industrial activities without adversely affecting the environment and depleting non-renewable resources.

The research field of industrial ecology is designed to achieve these objectives by using the biological system as an example. Nature has been able to evolve to an optimal state of resource and energy use over millions of years; a cyclical and cascading 'type III system' (see [2]). Our economy functions as a linear 'type II system' where some waste is reused or recycled but most waste leaves the system. The means that are being used to attempt to achieve a more closed industrial system include: closing substance, product or material cycles/chains, by diminishing the use of non-renewable resources, by avoiding emissions and waste, by reducing dissipative applications and so on.

It is clear that environmental scientists should study the economic chains that interact with the environment. Chain analysis is designed to determine the overall environmental effects of any specific change to a particular system, as a chain or network of human activities. Systems can be function-oriented or region-oriented [3]. Substance flow analysis clearly belongs to the region-oriented approach (see later on in the paper).

Besides the theoretical framework of industrial ecology, several analytical tools have been developed within the research field based on thermodynamics, systems modelling and natural ecology. Substance flow analysis [4] is one of these tools which can be applied to put the above-mentioned principles into practice. Other tools within this field are e.g. material flow accounting [5,6] and life cycle analysis [7]. These tools also have the purpose of analysing integrated chains, but the subjects of research are materials and products. The relation between economy and environment is viewed in physical terms only and each tool only describes a limited section of the relationship, thus only

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a limited view of the overall impact of economic chains is obtained. In the case of substance chains, only the relation between economy and environment for a single substance or a group of substances is described [8].

Van der Voet [9] defines substance flow analysis as 'an analytical tool which aims to provide relevant information for a region's overall management strategy with regard to one specific substance or a limited group of substances. In order to do this, a quantified relationship between the economy and the environment of a geographically demarcated system is established by quantifying the pathways of a substance or group of substances in, out and through that system'. The system can be the world, a nation, a region, a community, business sector, company or household. The flows are associated with specific environmental effects studied, allowing for an effective cause–effect modelling, by linking the actual industrial metabolism to specific environmental issues in a quantitative manner [10]. Substance flow analysis offers insight in the way a substance or a group of substances flows through our society. The tool helps us to understand the industrial metabolism of a specific substance by following the substance flows from their initial extraction or production, throughout their use by man in the economy and up to their ultimate disposal in the environment. To put it differently, the substance chain is studied following a region-oriented approach according to the principles of chain analysis.

The ultimate goal of applying substance flow analysis is to support policy by analysing environmental problems. The tool allows us to indicate the causes for environmental problems, to identify the most promising policy measures to reduce or eliminate them and to compare the effects of potential abatement measures.

In this paper, the results of a three-year project which investigated the possibilities to apply substance flow analysis in order to support environmental policy in Flanders are presented. This was performed by applying the model to chromium, cadmium and nitrogen compounds. More specifically, the chromium case study is further elaborated.

However, specifically for chromium, the project has shown that many difficulties exist in connection with the substance being studied—chromium—on the one hand and the region under investigation—Flanders—on the other. These limitations of applying substance flow analysis are highlighted further.

2. Substance flow analysis in the Flemish region of Belgium

Up to now there exists relatively little or no experience with the use of substance flow analysis in Flanders and Belgium. In the frame of the agreements made at the North Sea conferences, the Technical Commission for the North Sea has prepared substance reports for 36 priority substances, nitrogen and phosphorous [11]. In these reports, the emphasis is on the quantification of atmospheric and aquatic pollutant fluxes. Solid waste streams and substance flows within the economy are not or not systematically taken into consideration and the interdependencies among the different substance flows are not modelled. The substance reports are therefore emission inventories and not substance flow analyses. Emission inventories allow us to identify the economic activities that cause the undesired emissions and to focus policy measures on these economic processes in order to reduce or prevent their emissions. But emission inventories do not allow us, for example, to trace the economic origin of pollution problems or to asses the effectiveness of policy measures, especially for substances with a complex life cycle or a long lifetime in the economy.

In 1999 Vito, the Flemish Institute for Technological Research started a substance flow analysis project for the Flemish government. The aim of this project was to examine the possibility of using substance flow analysis to support policy in the Flemish region of Belgium. This was performed by applying the model to different substances, including heavy metals (chromium and cadmium) and nitrogen compounds. The work was concluded in September 2002 [12–16].

The developed model for substance flow analysis had to allow us to:

– Map and model the current substance flows in Flanders in a systematic way;
– Analyse and evaluate the mapped substance flow networks (e.g. in order to identify the direct, economic and ultimate origins of current pollution problems and potential sources of future environmental problems (current accumulations));
– Carry out simulation calculations in order to assess the consequences of autonomous developments and policy measures on the substance flow networks (e.g. in order to evaluate the effectiveness of potential policy measures aimed at emission reduction or pollution prevention).

A stepwise approach was applied based on the methodology for substance flow analysis developed by van der Voet [9] and ConAccount [17]. The methodological framework comprises the following three-step procedure:

1. Goal and system definition;
2. Inventory and modelling;
3. Interpretation of results.

All three steps involve making choices depending on the goal of the study.

The conclusions regarding the chromium case study will be discussed in this article. More specifically, our

practical experiences regarding the software and data collection will be elaborated on. The difficulties of constructing the bookkeeping account and substance flow model and the limitations of applying the model to the region of Flanders will be discussed thoroughly. It is not the object of this article to focus on the actual results of the case study, since the interpretation of the results requires much cautiousness due to important data gaps and data uncertainties.

3. Substance flow analysis of chromium in the Flemish region of Belgium

3.1. Goal and system definition

The goal of the study was to develop a model for substance flow analysis and to examine the possibility of using the tool to support environmental policy in the Flemish region of Belgium. This was carried out by first making a bookkeeping account, followed by setting up a substance model based on the bookkeeping data. In order to simplify the interpretation of the results, a sensitivity analysis and origin analysis were carried out. The goal of a sensitivity analysis is to assess the effect of data uncertainties; the origin analysis allows to determine the causes for the presence of the substance in problematic environmental flows. Finally, the effects of abatement measures were calculated in order to provide information about the most appropriate set of environmental policy measures.

The system definition primarily has to do with specifying four basic variables: substance, space, time and the distinction between the economy and the environment.

In order to define the substance flow analysis system, a choice for a certain *substance* or a limited group of *substances* has to be made. This choice is often inspired by known environmental problems within a region. The substance flow analysis discussed here has been applied to chromium due to its environmental importance for the Flemish region of Belgium.

Chromium is one of the priority pollutants because of its high toxicity, its widespread use and subsequent emissions and its accumulation in the environment. However, chromium toxicity is dependent on the oxidation state. Chromium primarily exists in nature in the trivalent and hexavalent oxidation states. Hexavalent chromium (Cr (VI)) is a highly soluble and carcinogenic metal whereas the reduced form (Cr (III)) is less soluble and non-toxic. This form is believed by many to play a nutritional or pharmaceutical role in the body, but its mechanism of action is unknown.

The source of chromium is chromite ore. Demonstrated reserves will last for centuries, whilst less economic, identified resources are sufficient to double that availability. One of the goals of integrated chain management, preventing resource depletion, is therefore not an issue, but pollution of the environment is.

Chromium is mostly combined with other materials because of its beneficial properties such as strength, hardness, permanence, resistance to temperature, wear and corrosion and so on. The areas of application are the ferro and non-ferro industry (alloys of chromium), the chemical industry (leather tanning, timber preservation, pigments, surface treatment…) and the refractory industry. The most important application—worldwide as well as in Flanders—is stainless steel. Chromium is also present as an impurity in phosphate rock and thus in fertilizer and fodder, in crude oil and hard coal [18].

The second demarcation to be made is a geographical one: the choice of a *region*. Any size from purely local to global is possible. However, a choice for an administrative region such as a country or a group of countries has definite advantages, especially with regard to data availability (production and trade statistics). This study was designed to look at the possibility to apply substance flow analysis in the Emish region in Belgium.

A third choice regarding the system definition concerns *time*. Studies on flows automatically imply a time dimension since substance flows are expressed in mass units per time unit. Usually a period of one year is chosen. This seems to be a suitable choice from the point of view of both data availability and policy formulation. The choice was made to collect data for 1998, the most recent year for which emission inventories were available when starting the study in 1999.

Finally, a distinction between the economy and the environment needs to be made. Differentiation of the substance flow network into subsystems is useful for interpreting the results in terms of the interaction between the economy and the environment. During this study, two *subsystems* were acknowledged, the societal and environmental subsystem [9]. It is also possible to distinguish the geological subsystem, but this was not part of the study. Geological substance flows occur on a geological time scale whereas substance flow analysis usually studies flows in a period of one year. The geological substance flows can therefore, be left out of consideration, while geological substance stocks are accounted for as ‘immobile stocks’ on the boundary between the societal and environmental subsystem. The societal subsystem, which is also referred to as the economy, the technosphere or the anthroposphere, contains stocks and flows that are mainly controlled or caused by humans. The environmental subsystem is also referred to as biosphere. This subsystem contains the stocks and flows in the environment.

Both subsystems can be divided into nodes (environmental compartments and economic processes). The environmental subsystem can be distinguished into e.g. the biosphere, atmosphere and hydrosphere. The economic subsystem can be distinguished into the various economic processes or industrial sectors in which the substance is used intentionally (e.g. in stainless steel) or is present non-intentionally (e.g. as an impurity in phosphate products). Table 1 shows the economic and environmental nodes taken into consideration for the substance flow analysis of chromium. For processes which occur on the boundary between economy and environment, a sound decision has to be made regarding the subsystem to which it belongs. It was decided that processes controlled by humans, namely crop production, waste treatment, waste incineration, compost treatment and sewage works are part of the economic subsystem. Landfill, (agricultural) soil, air, sediment, surface water and groundwater are considered to constitute the environmental subsystem.

Besides the substance flows between the different subsystems, the substance flows inside the subsystems (between economic processes or between environmental compartments) also have to be taken into consideration. A summary of the different subsystems, substance flows and stocks in the substance flow analysis of chromium in the Flemish region of Belgium for the situation in 1998 is schematically presented in Fig. 1

The substance flow diagram is divided into an economic and an environmental subsystem. Both subsystems have an inflow side (import) and an outflow side (export) from and to neighbouring regions. In addition, there is an interchange between the two subsystems: emission to the environment (e.g. industrial emission, product corrosion) and extraction from the environment (e.g. atmospheric deposition).

Both subsystems also include processes. They determine the distribution of the substance flows and their

Table 1
Processes in the economic and environmental subsystem studied in the substance flow analysis of chromium in the Flemish region of Belgium, 1998

Economic subsystem
Iron and steel industry, scrap trade, surface treatment industry, metallurgical industry, textile industry, leather industry, timber preservation, pigment and paint industry, glass industry, titanium dioxide industry, cement industry, vehicle industry, road traffic, graphic industry, electricity generation, petrochemical industry, phosphate industry, crop and grass production, fodder industry, animal production, food industry, households and other users, economic stock, waste treatment, waste incineration, compost treatment, sewage works
Environmental subsystem
Landfill, surface water, sediment, groundwater, agricultural soil, non-agricultural soil, air

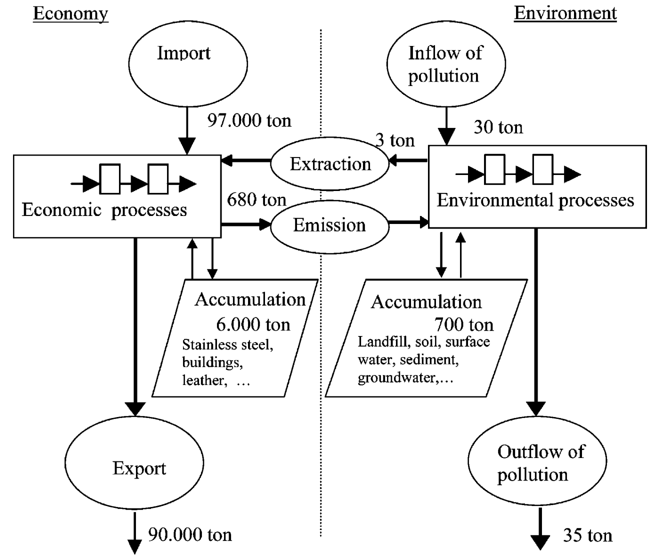

Fig. 1. Substance flow diagram for chromium in the Flemish Region of Belgium, 1998, divided into an economic and an environmental subsystem. Both systems include accumulation and processes, e.g. production, waste treatment, evaporation and leaching.

possible transformation. In the economy, this involves production, use and waste treatment. In the environmental subsystem, processes such as evaporation, leaching, deposition and sedimentation are concerned.

Economic and environmental processes transform products and materials from one state or compartment to another. When this transformation takes place within one year, the products and materials will appear as flows in the substance flow network. In case this transformation takes a longer time, the materials and products will appear as stocks or accumulation.

In the environmental subsystem, a distinction is made between the different environmental sections in which accumulation can occur, e.g. soil, water or sediment. In the economic subsystem, the accumulation consists of the stock of products and raw materials, due to the use of products which are not discarded in the same year as they were produced or imported.

The substance flow analysis method encompasses economic and environmental flows in a single system, so that the fate of the substance can be followed from its cradle, which is mostly economic, to its grave, which is usually environmental.

3.2. Inventory and modelling

3.2.1. Modelling

For the quantification of the overview of stocks and flows, two approaches were taken into consideration: bookkeeping and static modelling. Both techniques are discussed in more detail below.

The network of substance flows is modelled as a succession of nodes, each node representing an economic

or ecological process. Examples of flows are atmospheric deposition (from 'air' to e.g. 'non-agricultural soil'), use of textiles (from 'textile industry' to 'economic stock'), and etcetera. Inflows and outflows are balanced for every node and for the whole network, unless accumulation occurs [9].

3.2.1.1. Bookkeeping. Bookkeeping is keeping track of flows and stocks afterwards by simply registering them. Applying the mass balance principle allows estimating missing amounts. If the total inflow in one node does not equal the total outflow, this indicates the presence of accumulations or hidden flows, e.g. emissions or waste which were not (or not completely) registered [9].

Bookkeeping enables policy makers to point out problems, to spot trends and to evaluate the effects of certain changes ex post, including policy measures.

3.2.1.2. Static modelling. In static modelling, the substance flow network is modelled as a set of mathematical equations that reflect the relations between the in- and outgoing flows in the different processes in the network. The bookkeeping is therefore translated into a set of equations describing the flows and stocks as being dependent on one another. In order to do so, the relations between the various stocks and flows must be specified. Process characteristics such as emission coefficients, transformation output, partition coefficients, and etcetera can be usefully applied as coefficients in the systems equations. Analogous to the bookkeeping, the mass balance principle is applied in the systems modelling [9]. A limited amount of judiciously selected substance flows act as input variables in the model. The other substance flows can be calculated based on their relationship with these input variables.

Adding value to bookkeeping, static modelling allows policy makers to trace the origin of pollution problems (the direct causes, the economic origin and the ultimate origin) and to estimate the effectiveness of policy measures.

Each type of modelling has its own function, therefore, the choice for a certain type of modelling depends on the kind of information one wishes to obtain from the substance flow analysis. For the substance flow analysis of chromium, the goal was to identify hidden flows, trace back the origin of pollution problems and compare policy measures. Therefore, both bookkeeping and static modelling were appropriate tools.

3.2.2. Data collection

If available, data on the magnitude of both flows and stocks are used in a substance flow analysis. In most practical applications, the stocks however are ignored, and data collection is concentrated on flows only. This was also true for the chromium case study, since data on stocks are not or nearly not available. Even collecting data on flows turned out to be not obvious and very time consuming.

In order to quantify the substance flow network, several types of economic and environmental data are required:

- the amount of raw materials, commodities and waste, their origin and destination, and the content of chromium in these flows;
- the amount of chromium emitted to air, soil and water during the production, use and waste phase;
- transboundary in- and outflow of chromium to the environment, flows between different environmental compartments, and flows from the environment to the economy.

Environmental data were mostly obtained from public agencies. Regarding transboundary flows and emissions to air and water, most data were obtained from VMM, the Flemish Environmental Agency. Data about waste flows were mostly obtained from OVAM, the Public Waste Agency of the Flemish Region. Regarding the concentration of chromium in waste, various data from literature were used.

Very few economic statistics are available on the scale of the Flemish region in Belgium. Therefore, we decided to collect primary data by sending questionnaires directly to the Flemish industry and federations. This implied that the quantification process was very time consuming. Even more, the result of the quantification step was dependent on the goodwill of the industry and federations to cooperate. In very few cases, data could not be communicated due to its confidential nature but in most cases, industry and federations were willing to collaborate. In spite of this, many chromium flows could not be quantified because the information was not available at all. Missing data were e.g. the average concentration of chromium in a range of products, the amount of specific products consumed by the Flemish population in 1998 and the production quantities of some applications in Flanders. Other flows could only be quantified with a high uncertainty because many data are only available for all of Belgium, since most federations represent branches of industry on a national level. In this case, the data needed to be extrapolated to the level of Flanders, based e.g. on the number of inhabitants. If the industrial sector in question is not distributed over the different regions of Belgium, namely Flanders, Walloon and Brussels, according to a certain logic, we observed that it was very complicated to assign a certain percentage of a flow to Flanders.

Primary economic data were completed by secondary data, which included data from literature and extrapolation of literature data for other regions to

the region of Flanders, e.g. based on the number of inhabitants or on production quantities.

The consumption of products containing chromium was mostly extrapolated from literature regarding other European countries, again based on e.g. the number of inhabitants or on production quantities.

Figures which could not be obtained using the above-mentioned data sources were estimated by means of the mass balance principle. By applying this principle, inflows and outflows are balanced for every economic process or environmental node as well as for the system as a whole, unless accumulation within the system could be proven.

By combining data of several sources with often large margins of error, the possibilities for making well-founded statements about the substance flow network are limited. However, bringing together all available data also increases the possibilities in more than one way. The attempt to construct a complete bookkeeping account functions as a verification process. When a node is not in balance, data are investigated in more detail in order to identify the problem and possibly find a solution. Also, some flows can be calculated more accurately as the balancing flow in a node than by measurements. This is especially true for flows which accumulate in the economy or the environment. Finally, sometimes there is more than one possibility to calculate certain flows and when this leads to analogue results this is a reassurance that the flow is well quantified.

3.2.3. Data quality

It is obvious that the quality of the bookkeeping account, the chromium model and the various kinds of analysis applied to it, depends on the quality of the data on which these are based. Table 1 shows the economic and environmental sectors of which the chromium flows needed to be quantified for this study. About 200 flows were quantified during the inventarisation phase. During the course of the project, many problems arose regarding the data collection, as described above. Not all problems could be solved satisfactorily, leading to important data gaps and data uncertainties for the economic as well as the environmental subsystem.

Two economic sectors which probably hold large amounts of chromium flows and stocks and which could not be quantified at all, are the surface treatment industry and the metallurgical industry. While the production of steel and stainless steel in Flanders could be quantified very well, import and export of steel and stainless steel as raw materials and contained in semi-finished and finished products could only be quantified with large margins of error. Considering the major amounts of stainless steel which are used in society and the high chromium concentration in stainless steel, generally 18%, these flows can influence the outcome of the bookkeeping account and of the substance model substantially. Many data uncertainties also exist for the other economic sectors holding the largest amounts of chromium, namely the textile and leather industry, pigment and paint industry and timber preservation industry. Some industrial branches, such as the phosphate industry, electricity generation and petrochemical industry, could be quantified very well, but, although not negligible, they do not contain large amounts of chromium compared to the other branches. The most important environmental data gaps and uncertainties concern atmospheric deposition, leaching from dump sites and soil, concentration of chromium in waste and compost and flows of chromium between environmental compartments.

In other words, considerable uncertainties exist regarding a vast majority of the quantified flows, while some important flows could not be quantified at all. Quantifying errors was not part of the study, however, a qualitative description of the reliability of the data was given for every economic process or environmental compartment. A sensitivity analysis was also performed in order to investigate the importance of specific uncertainties and data gaps. The following paragraphs about the interpretation of the data should therefore, be understood from the perspective of keeping these data limitations well in mind.

3.2.4. Software

No ready-to-use software program exists to construct and analyse a substance flow model. Several software packages were tried during the course of the project. Finally, the bookkeeping account for cadmium and nitrogen compounds was modelled using MS Excel, the substance model was programmed in Dynflow, a tool in Matlab—Simulink[1] developed by CML [19]. For the chromium case study, the bookkeeping account as well as the substance model was modelled using MS Excel, mainly in order to investigate the possibility of constructing a static substance model in less time than would be necessary when using Simulink.

The bookkeeping account and the substance flow model are represented as a network of nodes. Nodes can be external to the system boundaries (import, export) or internal (nodes in the subsystems economy and environment, as shown in Table 1). The different flows are connected to each other in Excel, therefore a change in a variable is automatically updated in the complete bookkeeping account or substance model.

[1] Simulink is a supplement of Matlab software.

The bookkeeping account contains fixed values, namely the absolute size of flows and stocks. In the substance model, these fixed numbers are replaced by the mathematical relations between the flows. Flows can be fixed, variable or balancing flows. Fixed flows are independent of other flows and have a specific value. Variable flows and balancing flows are calculated based on other flows. Every node has to be balanced.

An example of a node modelled in MS Excel is shown in Table 2. The balancing flow in this example is the export of waste to other countries or to other regions in Belgium. The production of electricity was an economic sector for which detailed and accurate data was available.

Programming the model in MS Excel was found to be a fast and convenient way to carry out substance flow analysis. The substance model can be programmed very easily based on the bookkeeping account. MS Excel allows one to perform a sensitivity analysis, an origin analysis and to calculate the effect of potential policy measures without much effort. It also offers an immediate overview of the results of various analyses, which allows one to compare results easily.

3.3. Interpretation of the results

Based on the overview of substance flows and stocks, conclusions are made to support substance-oriented policy. The interpretation of the results consists of several tasks:

- defining which flows and stocks can cause problems regarding the environment or human health;
- investigating what the direct, economic and ultimate causes for these harmful flows and stocks are;
- exploring which flows should be regulated in order to reduce their magnitude;
- examining how effective potential policy measures will be.

Table 2
Example of a node for an economic sector modelled in MS Excel: production of electricity

In	kg Cr	From
Import coal	77.729	Import
Heavy fuel	22	Petrochemical industry
Incineration of wastewater sludge	898	Wastewater treatment plant
Out	**kg Cr**	**To**
Emission to air	435	Air
Emission to surface water	3	Surface water
Use of waste in construction	5.230	Economic stock
Use of waste in road construction	37.596	Economic stock
Use of waste in other applications	10.099	Economic stock
Export of waste to other regions/countries	25.286	Export

3.3.1. Directly from the overview

Some conclusions can be drawn directly from the overview based on the bookkeeping account. The overview of flows and stocks contains a great deal of information regarding the amounts of chromium but no information about their importance or harmfulness, which makes it difficult to precisely extract the desired information from it. Possibilities to evaluate the overview of flows and stocks directly, without additional information and without further calculation, are therefore limited, but nonetheless important.

One of the observations out of the bookkeeping account is that chromium particularly accumulates in landfills. Therefore, it is very important that leaching of chromium from dump sites to groundwater or surface water is avoided.

The majority of chromium in surface water and in the air is caused by transboundary inflow from neighbouring regions. This indicates that measures to reduce emissions to surface water and to the air in Flanders may not have a proportional effect to the actual presence of chromium in surface water and air, if efforts in neighbouring regions are not also increased.

Economic import and export of chromium is very large compared to the environmental import and export and to the flow from the economy to the environment. Since Flanders has an open economy, this is in accordance with the expectations. Almost all of the chromium imported to the economic subsystem and exported from the economic subsystem is caused by the iron and steel industry. Moreover, the inflow of chromium is larger than the outflow, indicating an important build-up of a chromium stock in the economic subsystem. Sooner or later this chromium will end up in the environment—via corrosion of products or as waste after use. Therefore, this stock can be considered a future risk for man and environment.

Despite the limitations of interpreting the overview without further investigation, general policy recommendations can be made regarding a substance-oriented policy, e.g. closing loops and reducing emissions to the environment

However, the interpretation of the results should be done while keeping in mind the restrictions of the collected data. In order to help visualise these restrictions and their possible effects on the outcome of the bookkeeping account and the model, a sensitivity analysis was performed.

3.3.2. Sensitivity analysis

A sensitivity analysis was carried out in order to investigate the effect of data uncertainties on the bookkeeping account as well as on the substance flow

model. Possibilities to draw conclusions from a sensitivity analysis of the bookkeeping account are limited, since changing a flow in one node does not influence all related flows in other nodes. The substance model is more suitable for this purpose, since changes in one flow affect all other related flows.

Flows can be subjected to a sensitivity analysis if there are important data uncertainties, if they represent a major amount of chromium or if they have an important influence on an environmental compartment or on other flows which are calculated based on them.

The sensitivity analysis for the chromium model showed that the iron and steel sector has a major influence on the outcome of the model. This was expected because the sector holds the majority of chromium in the economy. If the amount of chromium in the steel and stainless steel node changes, the total import, export and accumulation in the economic subsystem also changes proportionally. The impact on flows in the environmental subsystem is also considerable.

Another finding was that modifying the concentration of chromium in manure and artificial fertilizer and the uptake of chromium by crops, has an important influence on many environmental flows.

The choice for balancing items also has a large influence on the outcome of the substance model. If a balancing equation is not well chosen, this can lead to negative balancing equations in other nodes and to results which do not make sense. A sensitivity analysis is therefore also a verification of the choices which have been made regarding fixed flows, variable flows and balancing items when constructing the substance flow network.

3.3.3. *Origin analysis*

In order to pursue a substance-oriented environmental policy, insight into the origin of environmental problems is required. The origin of a substance flow was defined on three levels during this study, namely the direct, economic and ultimate origin [9]. The direct origin can be deduced directly from the overview. The economic origin is calculated by tracing the flow back to the responsible economic sector. The ultimate origin is calculated by tracing the flow back to the system boundaries. In order to trace the ultimate origin of a flow, the analysis needs to be applied to the substance model. Direct and economic origin analysis can also be performed based on the bookkeeping account.

The presence of chromium in products as such does not pose a risk for human health or causes environmental problems. When these products are discarded and end up as waste, however, harmful effects on human health and the ecosystem can occur. The substance can enter the environment, e.g. due to emission to the air during waste incineration and leaching from dumping grounds. The accumulation of chromium in society is therefore indeed a threat. The non-intentional use of chromium in agriculture causes environmental damage and ecotoxicological risks, as does the presence of chromium in surface water.

The following nodes are therefore considered as ‘problem areas’ and are subject to an origin analysis: crop and grass production, surface water, landfill and the economic stock.

Table 3 shows the results of the origin analysis for surface water.

Several important conclusions can be derived from the origin analysis, of which some are stated below. Seventy-five percent of the chromium in the crop and grass production is caused by non-intentional applications, of which the use of manure and artificial fertilizer in agriculture is the most important source. Sixty percent of the inflow of chromium to rivers in Flanders is caused by transboundary inflow, twenty-six percent by intentional and fourteen percent by non-intentional applications. Eighty-two percent of the inflow to dumping sites is caused by intentional applications, of which stainless steel is by far the most important. Intentional use of chromium is responsible for ninety-nine percent of chromium in the societal stock, again dominated by the stainless steel industry.

Performing an origin analysis is an aid to focus policy measures on those industrial sectors or applications which cause the most part of the presence of chromium in the above-mentioned problem areas.

Table 3
Origin analysis for the presence of chromium in surface water

Direct origin	
Soil (agricultural and non-agricultural) and air	13%
Industrial emissions, electricity generation, petrochemical industry, waste incineration, road traffic...	2%
Sewage works	3%
Corrosion stainless steel	6%
Landfill	16%
Transboundary inflow	59%
Households	1%
Economic origin	
Agriculture	13%
Consumers	3%
Industry (including waste incineration)	15%
Others (road traffic, construction, corrosion...)	9%
Non-economic origin (sediment, transboundary inflow...)	60%
Ultimate origin	
Import phosphate rock + phosphate products	8%
Import raw materials for iron and steel industry	17%
Import raw materials for other industry—intentional	9%
Import raw materials for other industry—non-intentional	4%
Import raw materials for electricity generation	1%
Import raw materials for petrochemical industry	1%
Transboundary inflow	60%

3.3.4. Policy measures

The substance flow model allows calculating the effect of future potential policy measures. When the actual values are assigned to the different input variables, the model calculates and analyses substance flows in the current situation, resulting in the same outcome as the bookkeeping system. By changing the values of the input variables or the process characteristics (fixed flows, emission coefficients, concentration of chromium in products…), simulation calculations can be executed. The calculation results in an equilibrium situation. Since the time dimension is not included when applying static modelling, no indication can be given as to when this equilibrium state will occur. The effect of measures on each flow can be looked at separately, e.g. in order to evaluate which environmental compartment is most influenced. It is also possible to calculate and compare the effects of different sets of measures, such as a continuation of the current policy versus additional and possibly more radical measures. Besides providing information on the effectiveness of potential abatement measures, problem shifting is also detected.

The following (fictional) basic set of measures was calculated for chromium: halving industrial emissions to water and air, extra purification in sewage works (50% less chromium emissions from sewage treatment to surface water, meaning more chromium is landfilled and incinerated), no more sewage treatment sludge to be applied to agricultural soil, 50% less chromium in artificial fertilizers, fodder and raw materials for the phosphate industry and halving the transboundary inflow through surface water. This basic set was compared with a set of additional measures, which consisted of the basic set plus halving the use of chromium in the pigment, paint, textile and leather industry, completed with a zero chromium content in artificial fertilizer, fodder and raw materials for the phosphate industry. Although the chosen measures are mostly fictional, they are based on current and future points of interest regarding environmental politics in Flanders and partly reflect the most likely measures which can be expected to be implemented.

The results showed that the basic set of measures as well as the additional measures hardly affected the flows in the economic subsystem. The basic set of measures did influence the flows in the environmental subsystem substantially. The largest reduction of chromium occurred in the agricultural soil (−50%) and surface water (−40%). The effect on air was less explicit (−25%) and the effects on groundwater, non-agricultural soil, sediment, sewage works and dumping sites were less pronounced. Introducing the additional measures almost doubled the reduction of chromium in agricultural soil (−90%) and also enhanced the effects on the other elements of the environmental subsystem, but less explicitly.

Particularly for chromium, a problem appears regarding the actual environmental and health benefits of potential policy measures. In this substance flow analysis project, no account was taken of the oxidation state of chromium. This distinction is difficult to make because of the lack of data on the one hand and the many possible conversions between Cr(III) and Cr(VI) in the environment on the other hand.

Chromium occurs mainly in three forms. Chromium metal does not occur naturally, it is produced from chrome ore. Metallic chromium (Cr(0)) is a steel-grey solid with a high melting point that is used to make steel and other alloys. Hexavalent chromium (Cr(VI)) is produced industrially when Cr(III) is heated in the presence of mineral bases and atmospheric oxygen (for instance, during metal finishing processes). Cr(VI) occurs in industrial effluents and is a biocide in wood preservatives and paints. It is this form of chromium that has proven to be of the greatest occupational and environmental health concern. Trivalent chromium (Cr(III)) occurs naturally in rocks, soil, plants, animals, and volcanic emissions. Cr(III) is used industrially as a brick lining for high-temperature industrial furnaces and to make metals, metal alloys, and chemical compounds. In the environment, a variety of different processes can effect Cr(VI) reduction and hence detoxification.

Calculating potential policy measures shows which flows and environmental compartments are affected and by what amount. However, without further investigation one cannot know how much of this amount consists of Cr(VI) and Cr(III). Since it is obvious that policy measures should be directed particularly at the most toxic form of chromium, a substance flow analysis in itself does not suffice to define the best possible set of measures, unless data about the speciation of chromium is included.

Another consideration to be made when evaluating policy measures is the possible beneficial effect of the use of chromium in certain applications. The tool, '*substance flow analysis*', does not allow one to detect problem shifting to other substances. Sometimes the use of chromium leads to a diminished use of other harmful substances or to a reduced release of other substances in the environment. For example, the presence of chromium in preserved wood reduces the leaching of arsenic to water and soil. Reducing the use of chromium in certain applications therefore, does not automatically lead to an improvement for the environment as a whole.

4. Substance flow analysis in policymaking

The main goal of the study was to investigate the possibility of using substance flow analysis in Flanders. The emphasis of the project was on a quantitative analysis of the substance flows in the region of Flanders. The most important outcome of the study discussed in this article was encountering the difficulties of applying substance flow analysis in connection with the substance chromium, on the one hand, and with the region Flanders, on the other. In the near future, a workshop will be held in order to sensitize policy makers, environmentalists and industry. How the results will be viewed and what the consequences of this study for environmental policymaking will be, is not yet clear at this time, shortly after the ending of the project.

On a more general level, we are also aware of the fact that detailed scientific analysis by itself does not suffice to accomplish the visions of industrial ecology, to 'learn' from nature how to conduct business in a sustainable way, meaning amongst others that less resources are used, less waste is produced and less emissions to the environment occur. Cohen-Rosenthal [20] says, 'The power of industrial ecology as a conceptual framework is not the description of mass flows and their consequences but in applying human intention to explore potential connections so that we create interactions with more value and less waste'. However, we feel that work on quantifying substance flows, more specifically on the possibilities as well as the limitations of applying this technique, is still needed. As Cohen-Rosenthal [20] says, 'Understanding what occurs is important; understanding what should occur is even more important'. This project, amongst others, has shown that applying the technique of substance flow analysis is not as straightforward as it may seem, depending on the substance which is studied and the region for which the analysis is performed.

5. Conclusions

Substance flow analysis is one of the analytical tools which concretize the concept of industrial ecology. More specifically, it helps to understand the industrial metabolism of a substance or a group of substances by quantifying and interpreting its pathway throughout the economy and the environment.

Based on the experiences described in this article, it is clear that applying substance flow analysis for environmental policy in Flanders has its possibilities, but also its limitations.

Quantification of the substance flow network is very time consuming. Also, there is a lack of economic data, while finding data specifically for the region of Flanders is even more complicated than for Belgium. Moreover, it must be stressed that the quality of the bookkeeping account and of the substance model can never be better than the quality of the data on which they are based. This is also valid for the other aspects of the substance flow analysis, which include the origin analysis and the calculation of policy measures.

As was mentioned before, for the chromium case study there are large data gaps regarding some industrial sectors and many flows can only be calculated with significant margins of error. The chromium case study is therefore an overview of all relevant data for the region of Flanders, which were available at the time of the study. If more and better data were available, the quality and reliability of the model would improve substantially.

Furthermore, the economy in Flanders is characterised as an open economy, which can imply difficulties for formulating and implementing appropriate policy measures, since policy and management inside the regional boundaries is not able to solve transboundary flow problems.

Performing a substance flow analysis to provide relevant information for the environmental policy is particularly suited for substances with complicated economic life cycles. In the case of chromium, however, the occurrence in oxidation states with a different toxicity adds additional difficulties to the use of substance flow analysis for defining the best possible set of measures. A substance flow analysis in itself does not suffice for this purpose, unless data about the oxidation state of chromium are included.

As for all substance flow analyses, problem shifting to other substances is also not detected and the possible beneficial effect of chromium use cannot be integrated in the model.

In spite of these limitations, substance flow analysis can play a role in environmental policy by providing relevant information for a region's environmental management strategy with regard to specific pollutants or groups of pollutants. It can be applied to regions of all sizes. However, an administrative region for which statistical data are collected—such as a country or a group of countries—has advantages.

The method of substance flow analysis gives insight in and an overview of the sometimes overwhelming amount of data and encourages strategic discussions about problematic substances.

Possibilities to evaluate the overview of flows and stocks directly are limited but nonetheless important. The overview provides a first insight into the size of the economic substance life cycle and the leaks from the economy to the environment, in an absolute as well as a relative sense. It also reveals the presence of hidden flows, allows one to calculate flows which are difficult to quantify and indicates options to close loops. There-

fore, some first general recommendations for a substance strategy can be made based directly on the overview.

By performing several kinds of analyses, substance flow analysis also enables policy makers to link environmental problems to their underlying origins, to estimate the effectiveness of certain abatement measures and to notice the possible occurrence of problem shifting connected with these measures.

The chromium case study is a first attempt to quantify the flows of chromium through economy and environment in Flanders. If more data becomes available in the future, they can be easily integrated in the substance model. A full update of the model is recommended after a period of 10 years, or earlier when major changes in the substance flows occur or when important data gaps can be quantified.

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